Conference Paper, Published Version

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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/100332

Vorgeschlagene Zitierweise/Suggested citation:
Cheng, Liang (2002): Prediction of Local Scour Below Ofshore Pipelines- A Review. In: Chen, Hamn-Ching; Briaud, Jean-Louis (Hg.): First International Conference on Scour of Foundations. November 17-20, 2002, College Station, USA. College Station, Texas: Texas Transportation Inst., Publications Dept.. S. 175-183.

First International Conference on Scour of Foundations, ICSF-1
Texas A&M University, College Station, Texas, USA November 17-20, 2002

Prediction of Local Scour Below Offshore Pipelines - A Review

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ABSTRACT

This paper presents a brief review on the development of numerical model for local scour below offshore pipelines. Emphasis is given to the models developed by the author over the last three years at the University of Western Australia. The models reviewed include a potential flow scour model, a lee wake model for equilibrium scour and a turbulent model for time dependent scour processes. The limitations of these models and future research efforts are also discussed.

1 INTRODUCTION

Pipelines installed on the seabed disturb the local flow field producing an imbalance in the local sediment transport that leads to scouring of the seabed. The scouring can leave the pipeline unsupported over sections that may extend significant distances. Suspended sections of the pipeline are susceptible to damages arising from environmental forces (wave and currents forces) or human activities (fishing trawl and anchor loading). The consequences of pipeline failure would be severe both economically and environmentally.

Scour at pipelines can sometimes be beneficial where pipelines laid on the seabed may bury themselves under storm conditions due to local scouring. This phenomenon is referred to as the self-burial of pipelines. The self-burial of the pipeline can minimise or remove completely the need to trench and backfill a pipeline. If the process of self-burial could be exploited, the costs associated with installing and stabilising a pipeline can be reduced significantly. The typical costs for pipeline stabilization are in the order of 1-2 millions of US dollars per kilometre both in the North Sea and the Australian North West Shelf.

Evaluation of local scour is a very important element of pipeline design. Typical questions to be answered in the design process include: (1) under what conditions local scour will take place; (2) what is the maximum scour depth; (3) how fast the scour hole will propagate along the pipeline once the local scour initiates; (4) what are the equilibrium span length and (5) what is the time scale required for the free span to develop.

Due to the obvious significance, local scour below a pipeline has been the subject of a number of investigations over the last three decades (e.g. Kjeldsen et al. 1973; Mao 1986; Sumer and Fredsoe 1990, Li and Cheng 1999, Li and Cheng 2001a, among others). Early studies of local scour below pipelines were mainly achieved through two-dimensional flume tests where local scour profile in the plane perpendicular to the axis of the pipe was measured. Issues regarding two-dimensional scour, such as onset of scour (Sumer and Fredsoe 1991), mechanisms of scour (Chiew 1990), scour depth (e.g. Kjeldsen et al. 1973, Sumer and Fredsoe 1990) and time scale of local scour (Fredsoe et al. 1992), have been studied experimentally. Detailed reviews on the state-of-art development of local scour research can be found in Whitehouse (1998) and Sumer and Fredsoe (1999) and will not be given here.

There is little doubt that model test is the most effective way to understand local scour process so far. However it does subject to some drawbacks. Apart from being expensive and time consuming, small-scale laboratory tests do suffer from scale effects because most of the scale-down models can not satisfy the similarity laws. There are several scale effects such as the pipe Reynolds number, pipe roughness, in-coming flow turbulence, etc. (Sumer and Fredsøe, 1999). The scale effects need to be considered when the experimental results are extrapolated to prototype situations. Unfortunately little is known about these scale effects and none of these effects have been studied in a systematic manner (Sumer and Fredsøe, 1999).

In contrast to the scale-down laboratory tests, numerical models of local scour around pipelines do not suffer from scale effects. Once the numerical model is developed, it can be applied to different environmental conditions including those that could not be modelled under normal laboratory conditions. It has been widely accepted that a good numerical model can certainly be complementary to model tests and can assist design engineers to identify the most crucial cases for which model tests may be conducted. The ultimate goal of numerical models will be to replace (at least partially) the costly physical model tests and to be used directly in the design of pipelines.

Development of numerical models for local scour below pipelines has been slow, despite of their relative significance. The numerical models developed so far are mainly for the two-dimensional scour in the perpendicular direction of a fixed pipeline, and can be roughly classified into two groups. One group uses potential flow model (referred to as potential flow model) and the other employs turbulent flow model (referred to as turbulent flow model). The details of these models will be reviewed in the following sections.

2 POTENTIAL FLOW MODELS

The pioneering research in scour prediction under pipelines was conducted by Chao and Hennessy (1972). Chao and Hennessy proposed an analytical method for estimating the maximum scour depth under offshore pipelines caused by sub-surface currents. The discharge through the gap between the pipe and the eroded seabed was estimated using a potential-flow model with the assumption of a flat seabed at any depth of scouring. It was assumed that when the velocity in the scour hole is greater than the free stream velocity, which is always specified as the critical velocity, erosion would occur. The maximum scour depth is reached when the velocity difference decreases with the enlargement of the scour section. The seabed shear stress is estimated by assuming that the seabed is flat and the flow in the eroded section resembles open-channel flow characteristics. The friction factor is determined using a Reynolds number type relationship. Since too many assumptions have been made in the derivation of the model, this method can only provide an order of magnitude estimate of the possible scour hole depth

Hansen et al. (1986) proposed a numerical method to simulate the shape of the scour hole under pipelines, based on the potential-flow theory. In their method the flow field was calculated using the modified von Müller method and the scour hole profile was obtained by a direct integration of the continuity equation for sediment transport. It was assumed that the bedload is the only form of sediment transport and the transport rate can be calculated using the Meyer-Peter and Müller formula. Although only the upstream part of the scour hole was calculated in the model, it was shown that the method predicts the scour depth under the pipeline and the shape of the upstream scour hole well.

Li and Cheng (1999) developed a curvilinear finite-difference model for calculating the maximum scour depth under pipelines. In this model, it was assumed that the flow field around the pipe is two-dimensional and can be analysed by the potential-flow theory. The equilibrium scour profile was obtained by an iteration methodology based on the Shields diagram. The main feature of the model was that it does not need to use any sediment transport formulae to calculate the shape of the scour hole. The comparison of the numerical results with the experimental data by Mao (1986) indicated that the model predicted the maximum scour depth and the upstream shape of the scour hole very well. However the model failed to predict the downstream part of the scour hole accurately. This was mainly because the potential flow model they used could not predict vortex shedding behind the pipeline, which is the main cause of the downstream scour below pipelines. Li and Cheng (1999) speculated that this could be improved if a turbulent model is used.

3 TURBULENT FLOW MODELS

Early numerical models based on k-ε turbulence models seemed to have difficulties to handle the seabed deformation due to scouring. Leeuwestein et al. (1985) developed a numerical model based upon the standard k-ε turbulence model and a sediment transport equation. A numerical package named ODYSSEE was used to calculate the turbulent flow field. As for the computation of the sediment transport and the variation in seabed topography they reported a failure in obtaining a real scour hole shape by using an empirical bed-load formula. This was ascribed to the ignorance of the suspended-load contribution in the model. In the numerical part of the investigation by Sumer et al. (1988), the so-called Cloud in Cell (CIC) method was employed to simulate the flow. It was reported that the CIC method generally gives good prediction on the gross characteristics of the organized wake behind the pipeline. However, there was no evidence in the paper showing that a numerical model was employed to calculate the seabed deformation. Instead, by comparing the effective Shields parameter with its time average value, an important conclusion was drawn that the organized wake behind the pipeline has strong effects on the profile of scour hole downstream of the pipeline. The time-averaged bed shear stress is not a suitable parameter to use in predicting the lee-wake scouring behind a pipeline.

Some improvements on k-ε based models have been achieved in 1990s. van Beek and Wind (1990) developed a numerical model based on the standard k-ε turbulence model and a transport equation for suspended sediment. The application of the model to scour prediction below a pipeline with and without an attached spoiler showed good agreement with the measured scour holes, although the predicted rate of erosion was three times as fast as in the physical model (Whitehouse, 1999). Brørs (1999) presented a model that includes the description of fluid flow by the standard k-ε turbulence and the suspended and bed-load sediment transports. Density effects were considered in the vertical momentum equation and in the turbulence equations. Flow around a surface mounted cylinder was predicted in good agreement with the experiments. However, in the scour calculation the model did not predict periodic vortex shedding, even during the later stages of scour development. The author suggested that a fine mesh (5000 nodes or more) is needed to predict the phenomena of vortex shedding. For the scour calculations, the prediction of a clear water scour hole agreed well with Mao's (1986) experimental measurements.

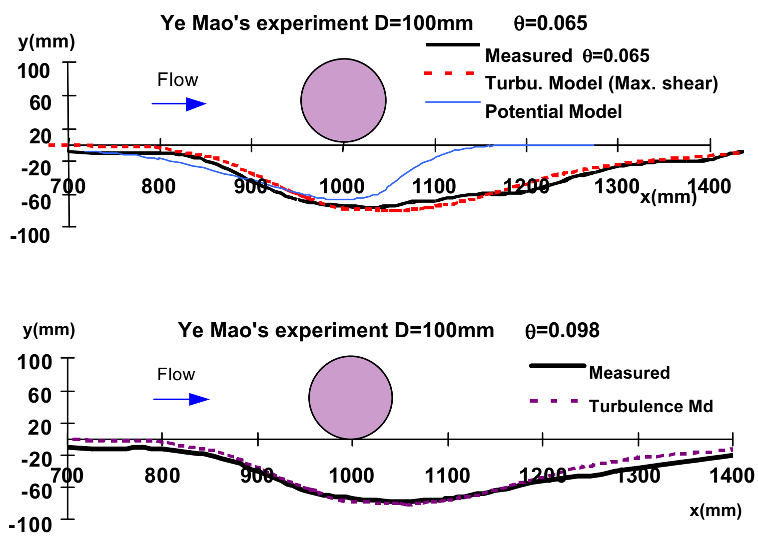

Fig 1 Predicted and measured equilibrium scour holes (Li and Cheng 2001a)

Li and Cheng (2001a) extended their potential flow model (Li and Cheng 1999) to include a turbulent flow model. The flow around the pipeline is simulated using a Large Eddy Simulation (LES) model that is capable of modeling the vortex shedding from the pipeline. The equilibrium scour hole is again determined by iterations, based on the assumption that the shear stress on the seabed is equal to the far field shear stress for live bed scour (or equal to the critical shear stress for clear-water scour) every where when the equilibrium scour hole is established (Li and Cheng 2001a). The iterative process of calculating the scour profile can be roughly described as:

1. assumption of an initial seabed profile;
2. computation of the flow field and flow induced seabed shear stress;
3. examination of the seabed shear stress assumption mentioned earlier;
4. if the seabed shear stress condition is not satisfied, adjust the seabed profile based the equations specifying the seabed shear stress assumption and go back to step 2;

5. if the seabed shear stress condition is satisfied, the seabed profile is the equilibrium scour profile.

It was found that the predicted equilibrium scour holes compared very well with the experimental results by Mao (1986). Fig. 1 shows the comparisons of the numerical results with the measured profiles by Mao (1986) for a pipeline being initially placed on the original seabed at two different Shields parameters. Fig 2 shows the comparisons of the numerical results with the measured profiles by Mao (1986) for pipelines initially placed above the seabed. The numerical results obtained using the potential flow model (Li and Cheng 1999) are also included in the figures for the purpose of comparison. It can be seen from these comparisons that the numerical model with a LES model predicted the equilibrium scour reasonably well for the both cases where the pipe was placed on the initial seabed and above the seabed. However the potential flow model failed to predict the downstream scour hole shapes accurately. This demonstrated that a correct flow model is very crucial in modeling the lee wake scour.

The advantages of the iteration model with a LES flow model are that the vortex shedding is modelled accurately and it does not use the empirical sediment transport formulae that normally contain empirical coefficients. The disadvantage of the model however is that it can not describe the time development of the scour hole due to the equilibrium assumption employed in the model.

In addition to the equilibrium model (Li and Cheng 2001a), Li and Cheng (2000) also developed a numerical model that is capable of modelling time dependent scour process. The model solves flow field using the same LES model as in the earlier work of Li and Cheng (2001a). The morphological change of the seabed was calculated using the non-equilibrium version of the general continuity equation in the same fashion as that used by Brørs (1999). The sediment deposition and entrainment rates were linked with the concentration of the suspended loads of sediment. The concentration of the suspended-load was calculated by solving the scalar transport equation of suspended-load concentration. The boundary condition for the near-bed concentration of suspended-load was specified using an empirical formula derived from experimental measurements (Zyserman and Fredsøe, 1990). The bedload

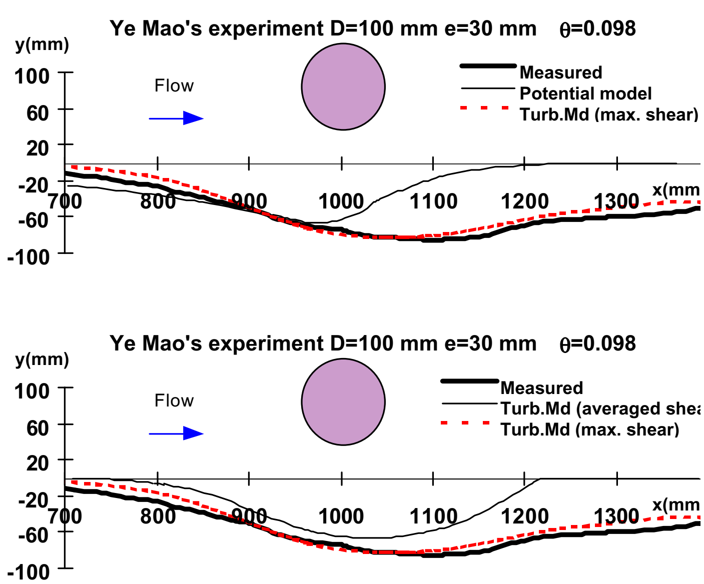

Fig 2 Predicted and measured equilibrium scour holes for a pipe initially placed above the seabed (Li and Cheng 2001a)

sediment transport was not included in the morphological model. Li and Cheng (2000) reported that this was because the inclusion of bed-load transport caused numerical instability at a rather early stage of the calculations. The reason for the numerical instability may be due to the fact that the bed-load transport under complex flow and bed slope conditions was not well understood. They argued, however, that the effect of neglecting bed-load transport on local scour is marginal for live-bed conditions. The argument was based on the experimental observation that suspended-load normally dominates bed-load under live-bed conditions. In addition, the use of the near-bed concentration formula by Zyserman & Fredsøe (1990) could partly take the bed-load transport into account in the calculation because the formula was derived from total transport rates (Zyserman & Fredsøe 1990). However, for large grain sediments and low flow rate situations bedload contribution to the scour process may be significant and further investigations are necessary. Fortunately most situations of engineering interests involve live bed sediment transport.

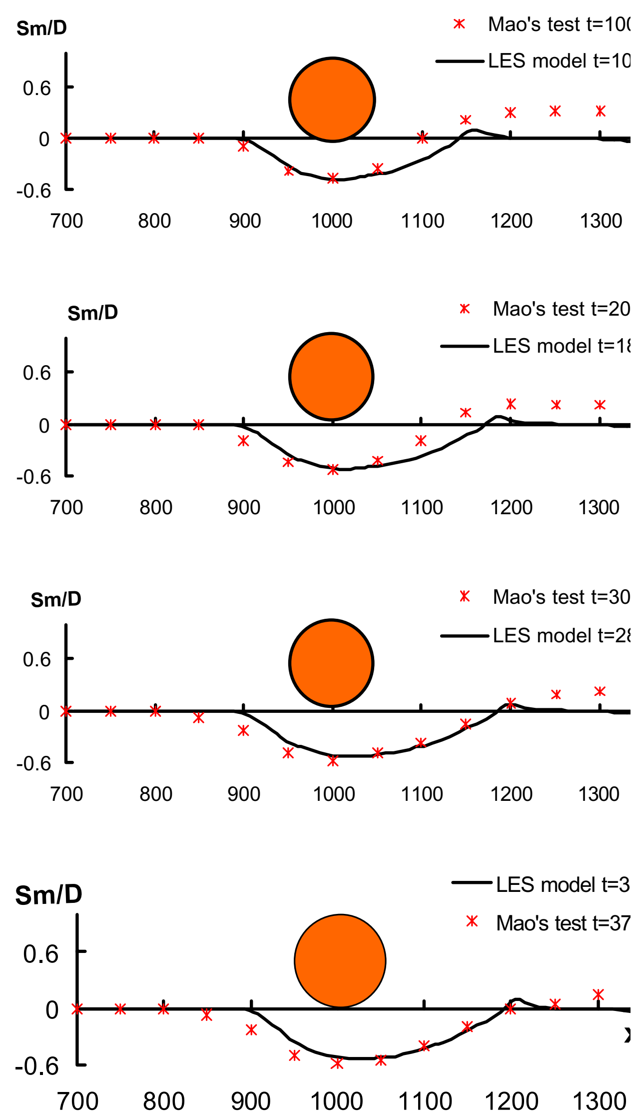

Fig. 3 Comparison of scour hole shapes, D=100 mm , e=0, θ=0.048 (Li and Cheng 2000).

The comparison of the numerical results with the experimental results by Mao (1986) indicated that the model worked quite well for both clear-water scour and live bed scour cases. Fig. 3 shows a clear water scour case and Fig. 4 gives a live bed case. It can be seen from Fig. 3 and Fig. 4 that there exist some discrepancies between the numerical and experimental results at very early stage of the scour. This was considered due to the ignorance of bedload sediment transport in the model. However the difference is noticeable only at early stage of the scour development. The numerical model does seem to predict the time scale of the scour corectly (Li and Cheng 2000).

Li and Cheng (2001) also developed a numerical model to simulate the scour deepening due to pipeline sagging. The model is very similar to the one they developed for time-dependent scour problems (2000), except that the bed load was included this model. In addition, a sliding mechanism was also introduced in this study. It was assumed that a small block of sediments can lose its stability and slide down along a slope if the slope of the scour hole at the point exceeds its angle of repose. This was implemented by moving the volume of soil at the area (where the bed surface angle is excessive to the angle of repose) to the nearest lowest location of the seabed. The conservation of soil volume was maintained in the soil relocation process.

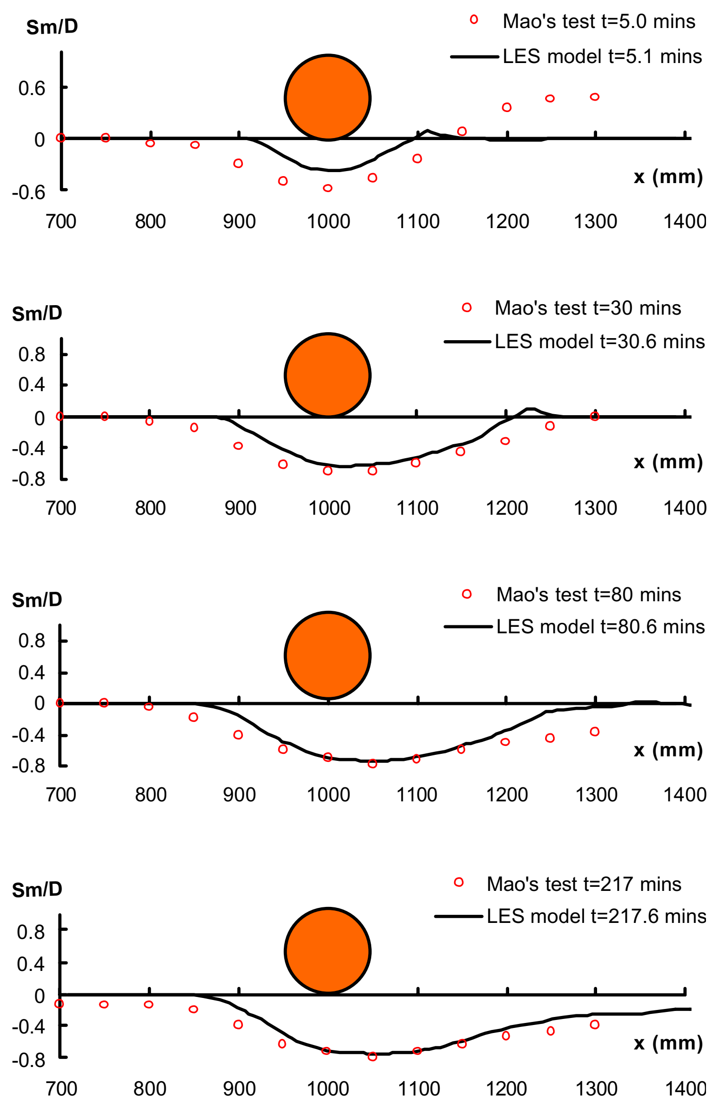

Fig. 4 Comparison of scour hole shapes, D=100 mm , e=0, θ=0.098 (Li and Cheng 2000).

The model was applied to investigating the scour deepening for different speeds of pipeline sagging. The comparison of the numerical results with the experimental results by Fredsøe et al. (1988) indicated that the model simulated the scour deepening due to pipeline sagging quite well (see Fig. 5).

4 DISCUSSIONS AND CONCLUSIONS

Evaluation of local scour is a very important element of pipeline design. Typical questions to be answered in the design process include: (1) under what conditions local scour take places; (2) how fast the scour hole propagates along the pipeline once the local scour initiates; (3) what are the equilibrium scour depth and span length and (4) how fast the scour hole develops.

Based on the above review, it is obvious that none of the current numerical models can answer all of these questions. The mathematical modeling of local scour below pipelines is still in its early stage. The numerical models developed so far are mainly concentrated on the two-dimensional scour in the perpendicular plane to the pipeline. The current two-dimensional models seem to be able to predict

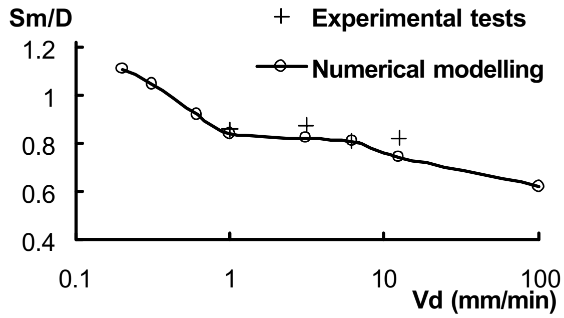

Fig. 5 Dimensionless final scour depth versus sagging speed (experimental data was taken from Fredsøe et al. 1988).

(i) the maximum scour depth due to steady currents (e.g. Hansen et al. 1986; Li and Cheng 1999);

(ii) equilibrium scour profiles due to steady currents (e.g. Li and Cheng 2001a);

(iii) time-dependent local scour processes of uniform sands subject to steady currents (e.g. Brørs 1999; Li and Cheng 2000)

(iv) time-dependent scour due to a moving pipeline in steady currents (Li and Cheng 2001);

The issues such as scour due to waves or combined waves and currents, onset of local scour, scour of non-uniform sands or cohesive sediments and three-dimensional scour, have never been addressed numerically. There is considerable amount of work to be done before numerical models can answer all of these design questions.

There seems to be no reason that the models developed for two-dimensional scour due to steady currents could not be extended to simulating local scour due to waves, the combined waves and currents and the three-dimensional scour. The research is being undertaken at the University of Western Australia to model the local scour due to waves. The rapid growth of computing power makes the development much easier than it has ever been.

ACKNOWLEDGMENTS

The work forms part of the activities of the Special Research Centre for Offshore Foundation Systems, established and supported under the Australian Research Council's Research Centres Program. The author would also like to acknowledge the supports from Australian Research Council through a Discovery Project DP0208223.

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